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A fibre-optic link for television outside broadcasts

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A FIBRE-OPTIC LINK FOR TELEVISION OUTSIDE BROADCASTS

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Summary

A video link using fibre-optic cable has many advantages over conventional co-axial links. A system which is light, compact and easy to install can be made which gives broadcast quality signals. However, the cost of rugged cable and connectors are too high at present (January 1981) for the system to compete with co-axial links.

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A FIBRE-OPTIC LINK FOR TELEVISION OUTSIDE BROADCASTS

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1. Introduction

Cables using optical fibres have many technical advantages over co-axial cables. At present they are more expensive however. Optical fibres are easy to install and can provide high quality pictures with little skilled adjustment. There is therefore a trade-off between the capital cost of the link and the recurring cost of installation. This report considers the pros and cons of optical fibres in the field of outside broadcasts.

Optical fibres are small and light and can carry high bandwidth signals with little attenuation. Their low loss and wide bandwidth allow a wide variety of signals to be transmitted with little noise or distortion. Because the cable is small and light it is easy to store and handle and can be routed in areas where other cables will not fit. This can lead to financial advantages. With a fibre-optic system rigging, storage and alignment are all simplified. As a result there will be savings in transport, storage space, rigging effort and engineers' time in alignment.

To ensure a high quality transmission it is preferable to transmit a frequency modulated (f.m.) signal. Suitable baseband links are difficult to engineer to the exacting standards of the BBC. However f.m. or digital modulation systems can be used. The fact in favour of an f.m. system is that the modulation and demodulation equipment are relatively cheap and readily available (although this argument may swing in favour of digital equipment in the future). Also an f.m. system can use the modulation and demodulation equipment in the standard s.h.f. link. This can lower the capital cost of the system and allows it to be used as an entrance link.

This report describes a fibre-optic link which transmits video signals on an f.m. carrier. It uses a conventional 70 MHz intermediate frequency, and can therefore be used in conjunction with s.h.f. links or separately as desired. The link uses a light-emitting diode (l.e.d) as a source and is capable of transmission over distances of about one kilometre. After that attenuation and dispersion increase the amount of noise.

An outline of the system and its expected performance will be given. Then the actual performance of the link as measured in the laboratory will be described. This will be followed by a description of some early field trials designed to obtain practical experience of using the link.

2. The Optical Link

The link was designed in such a way that it could provide a high quality video link with the minimum of adjustment. Electrically this meant that the signal-to-noise ratio (luminance weighted) should be of the order of 60 dB, and that differential phase and gain distortions should be of the order of 2° and 2% respectively. Mechanically, the cable had to be easy to rig (and therefore small and light) and capable of transmission over distances of the order of 1 km.

It is difficult to meet this specification using a baseband link without fine adjustment of the link in place. A frequency modulation system was therefore chosen with parameters identical to that of the standard terrestrial s.h.f. link to allow interchangeability of equipment and direct connections to be made. The f.m. parameters are given in Table 1.

TABLE 1

F.M. Parameters.

Intermediate frequency	70 MHz
Video deviation	8 MHz pk-pk
Pre-emphasis	CCIR Recommendation 405

2.1. Description and theoretical performance

The block diagram of the link is shown in Figs. 1 and 2. The video signal is transmitted along the fibre on an f.m. carrier which is itself amplitude modulated onto the optical carrier. The source of radiation is an l.e.d. whose drive current is modulated with the f.m. signal. The receiver is an avalanche photodiode (a.p.d.) which is driven by a constant current source which provides a small amount of automatic gain control (a.g.c). Standard pre-emphasis and de-emphasis networks increase the weighted signal-to-noise ratio of the system and minimise differential distortions.

For good performance the received optical

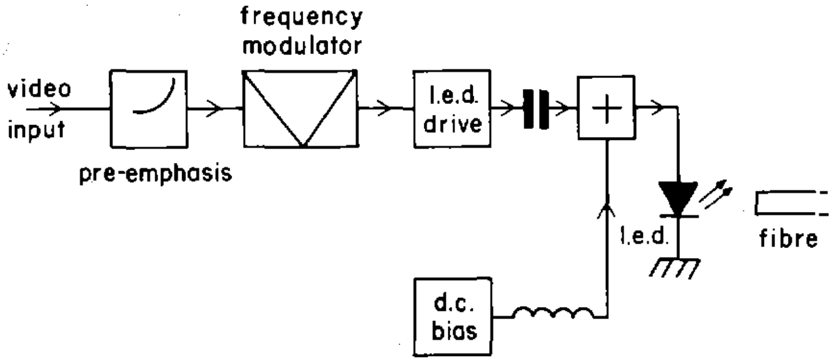

Fig. 1 - Diagram of Transmitter

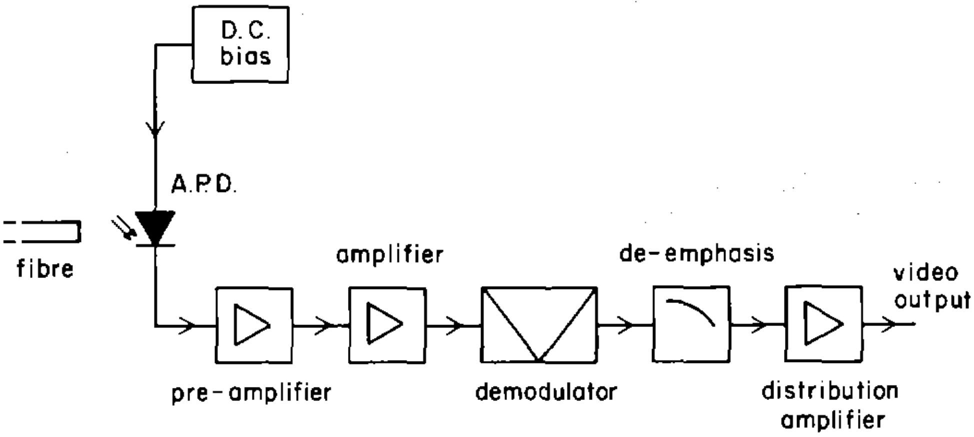

Fig. 2 - Diagram of Receiver

power must be greater than about 1μW. A full analysis of signal-to-noise ratios is confined to the Appendix. This shows that the signal-to-noise ratio of the demodulated signal will be 26.7 dB better than the carrier-to-noise ratio. As the noise on the carrier is mainly shot noise introduced by the a.p.d., we can calculate the expected noise power. For a typical system a received optical power of 1μW should be sufficient for a video signal-to-noise ratio of 60 dB (see the Appendix).

A received power of 1μW is obtainable using a high radiance l.e.d. and a normal optical system. 70 MHz is a little above the working range of many l.e.d.s. However l.e.d.s are made which will operate at frequencies up to 100 MHz and beyond. The device used was capable of launching 15μW of optical power at 900nm wavelength into a fibre with a 50μm diameter core. A system loss of 12 dB is therefore permissible. This loss could be due to fibre loss, connector loss or dispersion. The choice of fibre is restricted to a graded-index multimode fibre (step-index fibre has insufficient bandwidth and no suitable demountable connectors have yet been made for monomode fibre). Such a fibre may have a loss of 5 dB/km at 900nm and connectors each have a loss of 2 dB. Thus it appears that transmission over 1 km in three sections is possible. After that the loss may increase and it will depend on the circumstances whether or not the extra noise is tolerable. In practice material dispersion may reduce the maximum run to nearer 1 km.

For long distance transmission performance degrades. Optical losses and dispersion reduce the amplitude of the f.m. carrier and increase the noise. If better long distance performance is wanted from l.e.d.s then an increase in deviation will improve the signal-to-noise ratio. In a normal modulator the distortion will also increase so there is a compromise which must be reached. To reduce problems of bandlimiting caused by material dispersion then either long wavelength (1.3μm) sources can be used or the intermediate frequency can be lowered, or both. Long wavelength sources look attractive because fibre attenuation is low (say 1 dB/km) and material dispersion is negligible. As they are only just becoming available I have not investigated them. Lowering the i.f. is possible, but this results in non-standard equipment which is not attractive at present. However, if a long run is needed then lowering the intermediate frequency and using a higher power l.e.d. could produce a useful extension of the range.

The basic link is therefore suitable for circuits with a maximum length of between 1 and 1½ km. Because it uses f.m., and because the a.p.d. effectively provides its own a.g.c., the system can be installed and made to work without any adjustment. As the fibre optic cable is small and light it is easier to use than co-axial cable and therefore provides a significant advantage over existing systems.

2.2. Bench Tests

The system shown in Figs. 1 and 2 was built and tested (see Fig.3). The distortion of the signal was no worse than that caused by the modulator and demodulator (modem) back to back. The only extra impairment was noise.

The system worked satisfactorily for levels of received optical power between 1μW and 15μW. Within this range the system needed no adjustment. If the power is outside this range the a.p.d. tends towards breakdown at high gain (i.e. high voltage) and the high frequency response deteriorates at low gain. The constant current drive must therefore be adjusted in this case, but this is the exception rather than the rule.

Bench tests were performed to investigate the noise and distortion. The measured distortion of 2% differential gain and 2° differential phase was the same as for the f.m. modulator and demodulator back to back. The optical components must introduce negligible distortion therefore. Noise levels were higher than those observed in the back-to-back test.

It was expected that the luminance weighted signal-to-noise ratio would be about 60 dB for a 1μW optical input. This is shown in the Appendix. In practice the results depended on the a.p.d. One diode gave 59 dB and another 64 dB for a 1.4μW input (equivalent to 57.5 and 62.5 dB for 1μW input). Part of the difference between the results can be ascribed to losses in the interface between fibre and diode. However this is unlikely to account for more than 1 dB so the other 4 dB must be due to the difference in diode parameters.

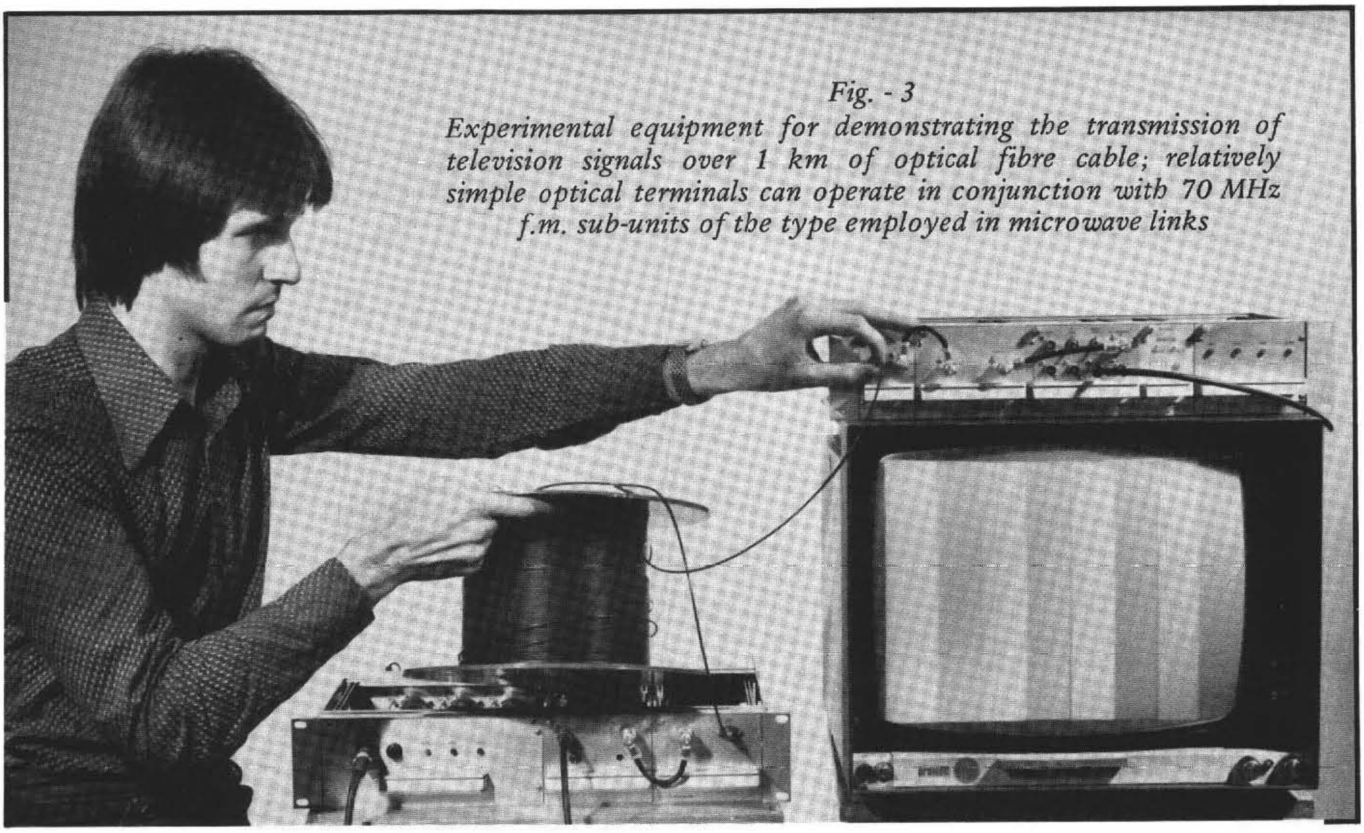

Fig. - 3
Experimental equipment for demonstrating the transmission of television signals over 1 km of optical fibre cable; relatively simple optical terminals can operate in conjunction with 70 MHz f.m. sub-units of the type employed in microwave links

The optical losses were then measured. The cable used was a graded-index multimode fibre with a 50μm core. The loss figure quoted by the manufacturers was 4.2 dB/km at 850nm. This is consistent with the less accurate measurement of 5 dB/km made in the laboratory using direct insertion loss (at 900nm) and time-domain reflectometry (at 850nm) methods.

Connections were made using a butt joint aligned using a jewelled ferrule. This technique is quoted as giving losses between 1½ and 2 dB, and indeed these figures were obtained using newly made connectors. The fibre is exposed to the outside world in this type of connector however, and is therefore subject to damage, abrasion and dirt. After normal laboratory usage the loss increased; typically to 3 dB per connector and in one case to over 5 dB. Polishing improves matters initially, but too much polishing allows the fibre to recess in the jewel making it a better dirt collector and hence increasing the loss.

Dispersion appeared to increase the loss at 70 MHz by about 2 dB over a kilometre. The effects of dispersion were investigated by measuring the frequency response of the system with different lengths of fibre. The differences can be ascribed to dispersion and the results are shown in Fig. 4. This indicates that dispersion is present, giving between 1½ and 2 dB loss at 70 MHz.

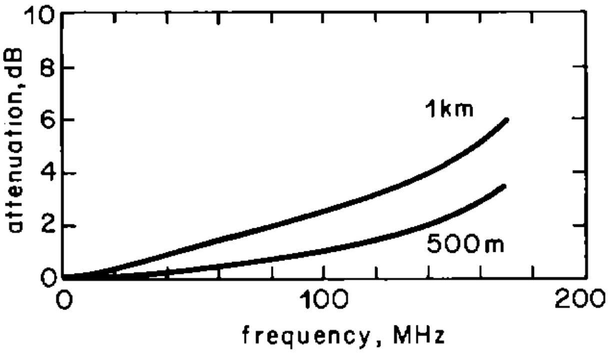

Fig. 4 - Effect of dispersion on the frequency response

The system is therefore capable of transmitting video signals over 1 km with a signal-to-noise ratio of about 60 dB. Under optimum conditions a signal-to-noise ratio better than this was obtained over 1 km with two intermediate connections. There was, however, little margin for unforseen losses. All the connectors became more lossy over the space of six months and so the performance became degraded.

If better performance is wanted other techniques are available. As mentioned before, increasing the deviation to 24 MHz improves the signal-to-noise ratio by 9 dB at the expense of an increase in distortion. This was verified experimentally. Lowering the intermediate frequency was also tried, but the l.e.d. used had insufficient bandwidth to transmit broadcast quality pictures.

3. Field Trials

The system described previously has been tested in the field. Two tests were performed in conjunction with Outside Broadcast staff in Manchester, and a third at BBC Research Department at Kingswood. This has provided a valuable insight into the benefits of optical links and the problems which may occur.

The aims of the tests were to ensure that the mechanical and electrical specifications of the link were adequate for use at outside broadcasts (O.B.). Laboratory work had shown the electrical specification of the link ought to be adequate but that there were reservations about the mechanical properties of the cable we were using.

The method of testing was to allow the equipment to be rigged by normal riggers at two O.B. sites: a football match and a department store. To fill an obvious omission, 500m of cable was also laid in the cable ducts at Kingswood. This gave us experience of most types of cable run that we would expect to meet i.e;

- along the ground,
- in cable ducts,
- on catenaries,
- over roofs,
- up the sides of buildings and
- in cable trays

The test confirmed that the electrical specification was adequate but that the mechanical specification needed revision.. Apart from a little radio frequency interference, the link gave a good clean signal at its output. The cable showed signs of weakness, however.

3.1. Electrical Performance

The electrical performance of the link was mainly satisfactory. The signals obtained over the link were noticeably clearer and crisper than those obtained over co-axial cable, and this was obtained with no adjustment of the link at all.

At one site in Manchester there was a noticeable degradation of the picture caused by radio frequency interference (r.f.i.). Our equipment was in a van containing the standard i.f. equipment for an s.h.f. link. This generated a high power signal at 70 MHz which was picked up in the first stage of the optical receiver, giving a characteristic interference pattern. This was ironical considering that fibre-optic cable is immune to r.f.i. The problem was later cured by shielding the input to the receiver.

The other problem was minor, being out of band noise. The demodulator had no output filter. As a consequence out-of-band noise in the region of 6 MHz to 15 MHz made waveform monitoring difficult. It was a trivial matter to remove this with a filter.

3.2. Mechanical Performance

The strength of the cable and the reliability of the connectors were not adequate for use on outside broadcasts.

The cable used was lightweight and therefore easy to rig. It was only 2.2mm in diameter and weighed 3.5 kg/km. This should perhaps be compared with a conventional co-axial cable - say Triax camera cable which is 14.5mm diameter and weighs 290 kg/km. Because the optical cable is light it was installed quickly and with little effort. One estimate of the time saved was 50%. Although this figure was not measured on a scientific basis, it is a good guide to the benefits which may accrue from using fibre-optic cable.

The cable was not strong enough for O.B. use. Its maximum stress was 800N. This could have presented problems if the riggers had decided to use their full weight on the cable during installation. Fortunately this was not necessary during the tests, although it will have to be allowed for if the system is put to regular use. The main problem was caused by the minimum bend radius of 25mm. There is nothing to prevent the cable from being bent too sharply, especially during installation when the cable is under stress. This showed up in the tests on a catenary between the mobile control room and a hook on a nearby wall. The tension required to remove the sag in the catenary bent the cable round the hook too tightly. Rather than the fibre cracking, the outer casing of the cable split allowing the fibre in its sheath to balloon free (Figure 5). Although the fibre did not break, reflectometer measurements indicate a loss of about ½ dB at that point.

A more rugged cable must therefore be used for outside broadcasts. The specification for this must ensure that the cable is strong enough to withstand reasonable accidental damage, but perhaps not gross negligence. The cable must perform the same tasks as standard co-axial cables but at the same time keep its size and weight advantages. As there does not appear to be a formal specification for the mechanical properties of co-axial cables in use in the BBC, the specification for a fibre-optic cable must be created from scratch. The following specification is tentatively proposed:

Mechanical strength	1.5kN
Crush test	5kN applied by two flat parallel plates 100mm long
Minimum bend radius	25mm
Weight	Less than 20 kg/km
Temperature range	– 20° C to + 50° C
Weather	The cable should be unaffected by immersion in water for periods less than one week.

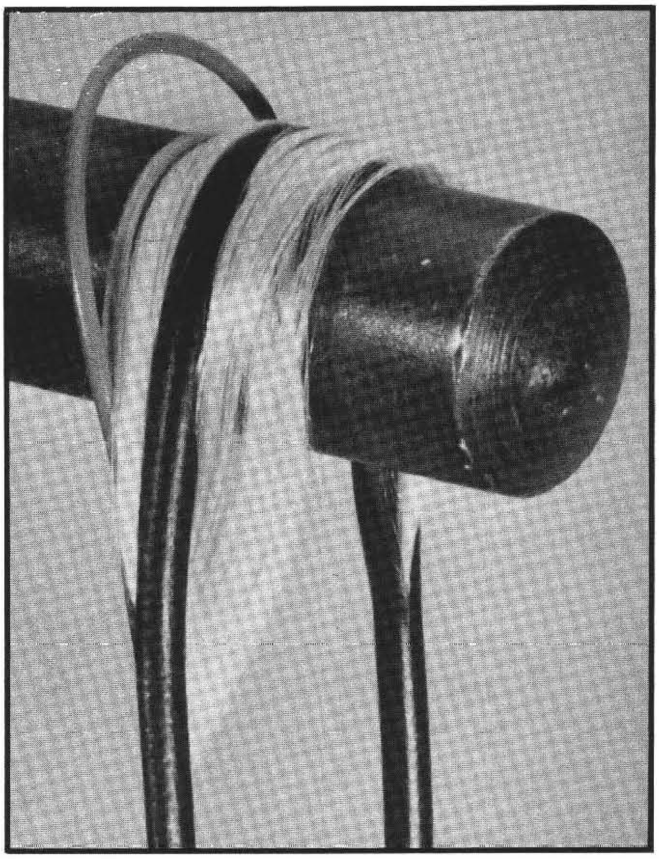

Fig. 5 - Damage to the cable caused by bending it round a hook

This specification should give a rugged cable which will withstand the normal rigours of installation and perhaps the occasional vehicle driving over it.

The connectors must also be rugged. The connectors in the field trials were of a type designed for laboratory rather than field use. The susceptibility of these devices to damage by dirt and abrasion was pointed out earlier in this report, and this was borne out in the field trials. It is my belief that any connector which works by butt jointing the fibres together is not suitable for O.B. use. This type of connection is tolerant of small amounts of dirt in the connector. Experience with electrical connectors has shown that it is not possible to keep connectors clean even with protective caps being used when the connector is not in use. The fibre-optic connector will soon become unusable therefore. One alternative is the expanded beam connector. In this fibre is protected by a collimating lens and the mating areas are larger. As a result the connector is more immune to dirt and therefore more reliable. At the time of writing these connectors were not readily available, and so confirmatory tests must be left for future investigation.

4. Future Prospects

It would be nice to say here that a fibre-optic system had been tried, found wanting, then improved and generally accepted, but that is not the case. It is possible to specify a cable and connector which would satisfy the needs of outside broadcast engineers. However it is not possible to obtain these components at a price which allows fibre-optic systems to compete with conventional co-axial or s.h.f. links.

The main reason for this is that these components although in existence are not yet in mass production. Until then the cost is likely to remain too high for serious consideration. However there is no obvious mass market, so any improvement may be slow.

In the meantime the link can be used with the lightweight cable in a protected environment, e.g. a cable duct. This is only likely to provide benefits if the link is temporary or if there is insufficient duct space for a normal cable. Fixed links can usually be engineered more cheaply from co-axial cables at present.

5. Conclusions

A link has been described which is capable of transmitting video signals over 1 km using an optical-fibre cable. The signal is good enough for high quality broadcast links.

Field trials have shown that the lightweight cable used is only suitable for use in a protected environment. More rugged connectors and cables are needed if the link is to be used in Outside Broadcasts, but these are not available at competitive prices.

6. Acknowledgements

The author would like to thank B.W. Potter and G.H. Walmsley for their assistance in the field trials in Manchester.

APPENDIX

SIGNAL-TO-NOISE RATIOS

This appendix derives the relationship between the optical power at the receiver and the signal-to-noise ratio of the demodulated signal.

First find the ratio of carrier and noise powers.

Suppose the received optical power is

$$p(t)^{*} = P_o\left[1 + f(t)\right] \qquad \text{A1-1}$$

where $$f(t) = \sin\left[\omega_c t + \pi\,\Delta f\int s(t)\,dt\right] \qquad \text{A1-2}$$

and $s(t)$ is our video signal

The mean received power in the electrical signal is then

$$\overline{i_s^{\,2}} = \left[\frac{P_o\, e\eta_a\, G}{h\ \nu}\right]^2 \overline{f(t)^2} \qquad \text{A1-3}$$

(assuming an arbitrary 1 Ω resistance)

There are two major sources of noise; thermal noise in the amplifier and shot noise on the current in the photodiode. Other noise sources can be neglected here. The shot noise is exacerbated by the avalanche characteristics of the a.p.d. and is given by

$$\overline{i_{NS}^{\,2}} = \frac{2\,e^2\eta_d}{h\ v}\ P_o\ B\ G^2\ F(G) \qquad \text{A1-4}$$

This is the normal shot noise on the photocurrent multiplied by a factor which accounts for the excess noise due to the avalanche process (F(G) often lies between 2 and 10).

The thermal noise is often more conveniently defined by an equivalent current at the output of the a.p.d. or input to the amplifier

$$\overline{i_{NA}^{\,2}} = \overline{i_{NE}^{\,2}}\,B \qquad \text{A1-5}$$

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*All symbols are defined in table A1.

Thus the ratio of carrier to noise powers is

$$\frac{C}{N} = \frac{\overline{i_s^2}}{\overline{i_{NS}^2} + \overline{i_{NA}^2}} \qquad \text{A1-6}$$

On demodulation the signal-to-noise ratio is improved as a consequence of the f.m. of the carrier. For an unemphasised signal the improvement is

$$\frac{S_v}{N_u} = \frac{3B\ \Delta f^2}{f_m^3} \cdot \frac{C}{N} \qquad \text{A1-7}$$

In addition, the effect of luminance weighting on a demodulated f.m. signal (which has a triangular noise spectrum) is to increase the signal-to-noise ratio by 12.3 dB for a signal with 5 MHz bandwidth. The use of pre-emphasis also gives an advantage of 0.8 dB. As most signal-to-noise ratios are measured relative to the picture (0.7V) rather than the video (1V) waveform we must reduce the figure by 3 dB.

Hence, combining several equations and correction factors.

$$\frac{S_p}{N_w} = 10.1 + 10 \log \left[\frac{\dfrac{3B\ \Delta f^2}{f_m^3} \left[\dfrac{P_o\, e \eta_a G}{b\ \nu} \right]^2 \overline{f(t)^2}}{\dfrac{2e^2 \eta_d P_o B G^2 F(G)}{bv} + \overline{i_{NE}^2} B} \right] \qquad \text{A1-8}$$

For a system with 8MHz deviation and in which thermal noise is low, A1.8 can be simplified

$$\frac{S_p}{N_w} = 26.7 + 10 \log \left[\frac{P_o \overline{f(t)^2}}{2b\ \nu\ B} \cdot \frac{\eta_a^2}{\eta_d F(G)} \right] \quad (dB) \qquad \text{A1-9}$$

If we insert a few representative figures

P_o = 1 μW

$\overline{f(t)^2}$ = ¼

B = 30 MHz

$F(G)$ = 5 A1-10

η_a = 0.6

η_d = 0.9

Then $\dfrac{S_p}{N_w}$ = 58.5 dB A1-11

It is possible that the function $\frac{\eta_{a}^{2}}{F\,(G)}$ could vary by as much as 4 dB either way.

This gives a range of possible results, and it is difficult to be conclusive as η_{a} and $F\,(G)$ are not often quoted in technical data. As a rough working figure we can say that we need just more than 1 μW of received power for a signal-to-noise ratio of 60 dB.

Table A1 List of Symbols

B	Bandwidth of f.m. signal
$\frac{C}{N}$	Carrier-to-noise ratio
e	Electronic charge
$F(G)$	Noise factor of a.p.d.
$f(t)$	f.m. signal
f_{m}	Maximum video frequency
G	Gain of a.p.d.
h	Planck's constant
$\overline{i^2_{\mathrm{NA}}}$	Thermal noise equivalent current
$\overline{i^2_{\mathrm{NE}}}$	” ” ” ” in unit bandwidth
$\overline{i^2_{\mathrm{NS}}}$	Shot noise current
i_{s}	Signal current
$p(t)$	Instantaneous optical power
P_{o}	Average optical power
$\frac{S}{N}$	Signal-to-noise ratio: subscripts refer to video or picture signal, weighted or unweighted noise
$s(t)$	Video signal
Δf	Peak-to-peak f.m. deviation
η	Quantum efficiency of a.p.d (subscript a for a.c.; d for d.c.)
ν	Optical frequency
ω	Angular frequency of f.m. carrier

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